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ScienceDirect
Renewable and Sustainable Energy Reviews
11 (2007) 923–936
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Development and applications of solar-based thermoelectric technologies

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Received 31 May 2005; accepted 17 June 2005

Abstract

In this paper a survey of solar-based driven thermoelectric technologies and their applications is presented. Initially, a brief analysis of the environmental problems related to the use of conventional technologies and energy sources is presented and the benefits offered by thermoelectric technologies and renewable energy systems are outlined. The development history of solar-based thermoelectric technologies is introduced together with the discussion of the existing drawbacks of current systems. Typical applications of the solar-driven thermoelectric refrigeration and the solar-driven thermoelectric power generation are presented in order to show to the reader the extent of their applicability. The application areas described in this paper show that solar-driven thermoelectric technologies could be used in a wide variety of fields. They are attractive technologies that not only can serve the needs for refrigeration, air-conditioning applications and power generation, but also can meet demand for energy conservation and environment protection.

Keywords: Solar-driven thermoelectric refrigeration; Solar-driven thermoelectric generator; Solar-based driven thermoelectric technologies; Pv

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2005.06.008

Contents

1. Introduction

Peltier effect and Seeback effect were first discovered to present in metals as early as 1820s–1830s, but the low thermoelectric performances of metal made these two effects fall on deaf ears all the time. Until 1950s, the advent of doped semiconductor materials with small band gap, which were found to have much bigger thermoelectric performances than the pure metals, revived the interest in this field. The exploitation of the thermoelectric applications soon became a new hot research subject in USA, Europe and Japan. Revolutionary developments first occurred in the US space program, the thermoelectric generators have been used by National Aeronautics and Space Administration (NASA) of USA to provide electrical power for spacecraft since 1961 [1] because of no moving parts, no position-dependence, more than 100,000 h steady-state operation, precise temperature control to within $\pm 0.1\,^{\circ}\mathrm{C}$, and adaptability for various sources and types of fuel. Later on, the thermoelectric device was developed to be as a thermoelectric cooler in the train carriage during summer while the same device can be used as a heat pump for train carriage heating during winter [2–4]. Over the past four decades, the thermoelectric devices have been used practically in widespread fields with the development of new thermoelectric materials with higher Peltier coefficients and increased COP [5]. S.B.Riffat and Xiaoli Ma introduced in detailed the present and potential applications of the thermoelectric devices [6]. Comparative investigation between thermoelectric devices and other devices have also been made. S.B.Riffat and Guoquan Qiu compared the performance of three types of domestic air-conditioners, namely the Vapor Compression Air Conditioner(VCAC), the Absorption Air-Conditioner(AAC) and the Thermoelectric Air-Conditioner(TEAC) [7]. P.K. Bansal and A. Martin made a detailed comparative study of vapor compression, thermoelectric and absorption refrigerators [8]. They all concluded that thermoelectric systems have a large potential market for small enclosures where the power consumption would be low, or safety and reliability would be important [7,8].

In recent years, the global increasing demand for refrigeration, e.g. air-conditioning, food preservation, vaccine storages, medical services, and cooling of electronic devices, led to production of more electricity and consequently more release of CO_2 all over the world. The International Institute of Refrigeration in Paris has estimated that approximately 15% of all electricity in the world is used for various kinds of refrigeration and types of air-conditioning, and the energy consumption for air-conditioning systems has recently been estimated to 45% of the whole households and commercial buildings [9]. The accelerated consumption of fossil fuels now has been recognized to cause serious environmental and energy problems such as global warming, ozone depletion, atmospheric pollution, and worldwide shortage of energy. By reason that the thermoelectric devices have promise as a power-generation system by utilizing solar thermal power and waste heat, and are friendly

to the environment as no any refrigerant gas is used, the development of thermoelectric applications became the worldwide focal point for concern again.

The thermoelectric devices can convert solar energy into a temperature difference to act as coolers or heater with the help of PV arrays, and also the thermoelectric devices can convert solar thermal energy from temperature difference into electric energy to act as power generators. Using solar energy to power the thermoelectric devices is thought to be an attractive way to serve the needs for refrigeration, air-conditioning applications and power generation, and simultaneously meet demand for energy conservation and environment protection. In past decades, much work has been reported on solar-driven thermoelectric devices. In his paper, an overview of the development solar-based thermoelectric technology will be given.

2. Solar-driven thermoelectric refrigeration

The theory of thermoelectric power generation and thermoelectric refrigeration was first presented by Altenkirch [10] in 1909. Thermoelectric industry developed rapidly along with the advent of new thermoelectric materials with high thermoelectric performances in 1950s. However, close attention was paid to solar refrigeration until the energy crisis in 1970s. Research in a Peltier's cooling effect integrated with PV also developed at that time [11], primarily for the cold chain project of the World Health Organization (WHO) and the international Health Organizations [9].

PV technology is usually used to provide the power for the solar-driven thermoelectric refrigeration systems. There are two types of solar-driven thermoelectric refrigeration systems with two different modes of thermal energy storage. One is solar PV/battery thermoelectric system, and another is solar PV/phase change materials(PCMs) thermoelectric system. A typical configuration of a solar-driven thermoelectric refrigeration system is shown in Fig. 1.

The solar PV/battery thermoelectric refrigeration is first developed. The main components of the system are the PV cell(including the PV array, the storage battery, the controller), the thermoelectric refrigeration system, and the cooled object (e.g., a cooling box). The PV array, which produces DC electricity when exposed to sunlight, is the most expensive component in the system. It is installed outdoors away from shadows, usually in the house roof and tilted towards the equator by an angle equal to the latitude of the location. The storage battery stores the excess electricity produced during sunshine

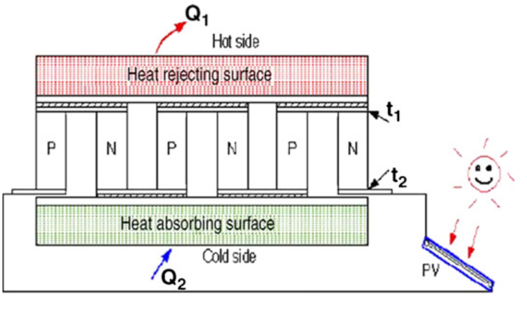

Fig. 1. Schematic of solar-driven thermoelectric refrigeration system [9].

periods. This stored energy is used for running the refrigerator during nights, cloudy and rainy days. There are specially designed lead-acid batteries suitable for deep discharge cycles occurring in PV systems. The controller is an electronic device, which controls the system operation according to the state of charge of the battery. Its main duty is to protect the battery against excessive charging or discharging [12].

For the solar-driven thermoelectric systems, the performance of whole system (η_{system}) can be written as the product of the performance of the thermoelectric refrigeration system(COP) and the PV efficiency (η_{PV}), that is,

$$\eta_{\text{system}} = \text{COP} \times \eta_{\text{PV}}$$

The COP of the thermoelectric refrigeration system reported is usually less than 0.6, and the η_{PV} average 10%, so the η_{system} of a solar-driven thermoelectric system is usually less than 0.06.

Wimolsiri Pridasawas compared detailedly the performance and available applications of the solar PV/battery thermoelectric refrigeration and other eight solar-driven refrigeration systems [9]. Compared to other solar-driven refrigeration systems, the solar PV/battery thermoelectric refrigeration systems have the following features: no working fluid and no moving parts, quiet, small size and light weight, but low COPs, difficult to achieve a low refrigeration temperature, and low reliability especially when the power supply is cut. The paper concluded that solar thermal-driven air-conditioning systems are attractive in many regions due to the increase of the cooling demand. The PV-driven thermoelectric cooling systems are mainly designed for mobile refrigeration purposes. Currently, there are many commercially available mobile units such as cooling boxes. The efficiency of a PV-driven thermoelectric cooling system depends on the insolation, the solar collector or the PV efficiency and the refrigeration performance. The economical advantage of this kind of system is still obscure due to the high installation cost. This system would be a long-term cost saving system since the energy source is free and the solar sub-system generally requires little maintenance. New refrigeration technology based on solar energy has not attracted much of the commercial refrigeration and air-conditioing industry so far. The development and production of such equipment is a future business possibility.

In the past years, many work have been done in this field to improve the efficiency of the solar PV/battery thermoelectric refrigeration system. NASA and other space organizations started a dual-use technology project to develop solar-driven refrigeration technology. This project worked on the application of the solar-driven refrigeration technology both on earth and in space [1].

H. SOFRATA proposed an effective heat rejection method for the hot side of thermoelectric modules to enhance the performance of a laboratory thermoelectric refrigerator and its solar power supply. The author first made a complete investigation on the natural convection of a solar-driven thermoelectric refrigeration system, and then compared the performance of three heat rejection alternatives, that is, single fan, double fan and natural chimney draft heat rejection. The experimental results showed that the natural chimney draft heat rejection can efficiently improved the performance of the system, and the expensive fan current can be used for cooling instead of wasting its power for heat rejection fans [13].

Y.J. Dai developed a small solar PV/battery thermoelectric refrigerator to meet the needs for outdoor use (2–3 persons). Two panels of solar cells available from Gofly Green

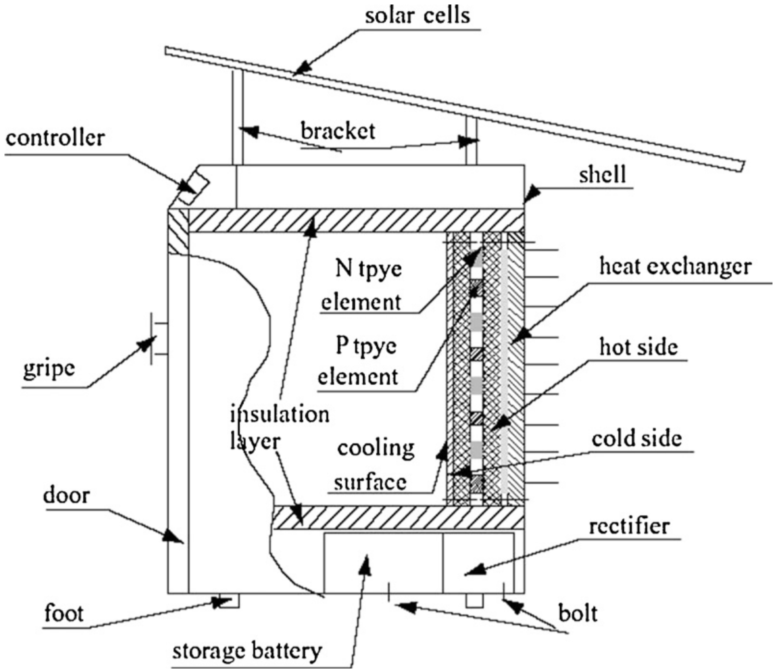

Fig. 2. Schematic of solar PV/battery thermoelectric refrigerator(prototype) [15].

Energy Co. Shanghai, are used in the experiment. For each panel, the area is $0.4m^2$, and the efficiency of energy conversion is 13%. The thermoelectric refrigerator consists of a thermoelectric cooling module, whose specific input power is 45 W, and specific voltage is 12 V. The lead acidtorage battery has a capacity of 100 Ah, and can supply electric power for 24 h without sunshine. It is reported that the unit could maintain the refrigeration temperature at 5–10 °C, and has a COP of about 0.3, furthermore, the performance of the system is strongly dependent on intensity of solar radiation and temperature difference between hot and cold sides for the thermoelectric module, etc[14,15]. Prototype of this system is shown in Fig. 2.

For a solar PV/battery thermoelectric refrigeration system, the installation cost of the PV cells is too high for local to afford, and certain advanced technical knowledge may be required in order to run the systems. Furthermore, the refrigerator has to operate all the time, so the storage battery is necessary. Otherwise, the electric power must be needed. The storage battery generally costs about 30% of the whole solar-driven thermoelectric refrigeration. As a result, the solar PV/battery thermoelectric refrigeration system have existed for several decades, but have only been used in limited applications. Currently most of the PV/battery-thermoelectric-refrigerators are only used for vaccine storages and medical services, or for mobile refrigeration purposes, but along with the advent of new thermoelectric materials and the development of thermoelectric technology coupled with the decreasing cost of PV, the PV/battery thermoelectric refrigeration is expected to be in more great use.

To make solar-driven thermoelectric refrigeration become a practical technology, a highly effective vacuum panel technology was originally developed to minimize heat leaks

into the cold volume by Oceaneering Space Systems, Marlow Industries, and Owens-Corning. An advanced solar-driven thermoelectric refrigerator/freezer incorporated the ''state-of-the-art' in thermoelectric refrigeration systems, vacuum panel insulation and phase change materials, was developed to use on NASA's International Space Station in 1993. Later on, the above companies predicated that a thermally efficient ''super-insulated'' cabinet using thermoelectric cooling and insulation systems, coupled with phase-change thermal storage materials, could be viable in the commercial market [16].

Many recent efforts have focused on a ''PV direct'' design, in which the PV/battery system was replaced by a PV/PCMs system in order to reduce the expense, efficiency loss, and mass associated with intermediate power conditioning and storage devices. PCMs has several attractive features, mainly the use of a heat that is stored in a material at a fixed temperature (i.e. melting temperature) and its high energy density. In this PV/PCMs thermoelectric refrigeration system, the PV panel was connected directly to the hot side of the thermoelectric cooler, and the PCMs was mounted in the cold side of the system to substitute as the storage battery in a PV/battery thermoelectric system for thermal energy storage. This kind of system is appropriate for thermoelectric cooling and refrigeration units which require precise temperature control. The schematic of a thermoelectric refrigeration system employing PCMs integrated directly with the thermoelectric cooler is shown in Fig. 3 [17]. Johnson Space Center [16] reported that the PV/PCMs thermoelectric refrigerator had the advantage of simplicity and low cost, but the COP of the total system was only 0.04. University of Massachusetts Lowell (2002) carried out a Solar Engineering Program entitled Design of a Standalone Portable Solar-Powered Thermoelectric Vaccine Refrigerator using Phase Change Material as Thermal Backup to design a portable vaccine refrigerator for remote villages with no grid electricity [18].

Recently more close attention was paid to the development of new PCMs [17] and numerical simulation of latent heat thermal energy storage systems [19–21]. All these works will be great favor of the development of the PV/PCMs thermoelectric refrigeration system.

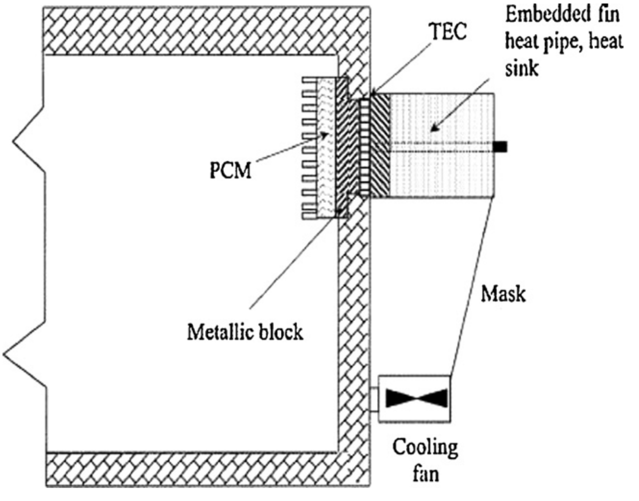

Fig. 3. schematic of a thermoelectric refrigeration system employing PCMs [17].

Compared to thermoelectric refrigerators and solar-driven thermoelectric refrigerators, fewer thermoelectric air-conditionings and solar-driven thermoelectric air-conditionings are reported. The service temperature is generally 15–20 °C for a air-conditioner system, so the cooling capacity required is higher than a refrigerator system and energy removed from the cooling side has a low potential to convert to a useful energy. The reported solar-driven thermoelectric air-conditioners were all applied in the cases in which the cooling capacity required is low, or the expense is not the main consideration (such as military or aerospace applications).

S.B. Riffat and Guoquan Qiu detailedly compared the performance of three types of domestic air conditioners, i.e., the vapor compression air conditioner, the absorption air conditioner and the thermoelectric air conditioner. It was concluded that thermoelectric air conditioners have many advantages, such as being completely CFC free, lightweight, high reliability, silent operation, fast start-up, easy control and wide operating temperature (−40–70 °C). Furthermore, the operating mode of a thermoelectric air conditioner can easily be changed, from a cooling mode to a heating one, by reversing the direction of the electric current. The main drawbacks of thermoelectric air conditioners are low COPs and high capital cost [7]. Excepting for having all above advantages and disadvantages, the solar-driven thermoelectric air conditioners can use renewable energy but higher capital cost because of the use of PV. Although the ultimate configuration of the solar-driven thermoelectric air conditioners is still developing, the open questions are being addressed and good progress has been made, but the cost is still the largest obstructive factor in the commercial success of the solar-driven thermoelectric air conditioners.

Mei et al. first developed a solar-assisted thermoelectric technology for automobile air conditioning [22]. Jorge Vázquez, et al. proposed a new concept for an active thermal wall based on thermoelectricity to improve the current practice of design and installation of air conditioning for enclosed spaces. The wall consists of two main components: the thermoelectric chains driven by conventional electric grid or photovoltaic cells, and the material where the thermoelectric chains are imbibed, as shown in Fig. 4. The active thermal wall works like an active thermal insulator keeping the temperature of the enclosed space to the value required taking into account the temperature of the outer environment. This new wall is subsidiary to the classical air conditioning systems, can make better use of the energy needed. The performance of the wall was analyzed and the possibility of applications in a greenhouse and a student residence building in Spain was numerically evaluated [23]. It was reported that the active thermal wall is possible to be

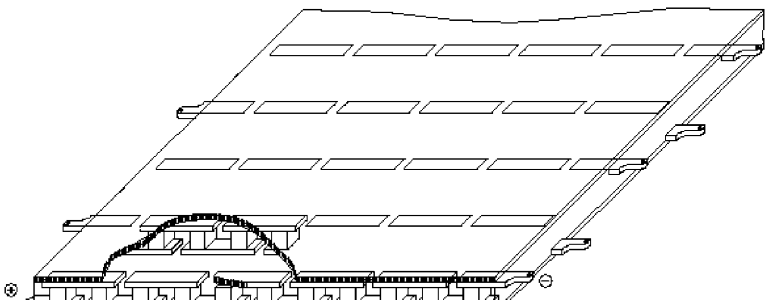

Fig. 4. Schematic of the active thermal wall [23].

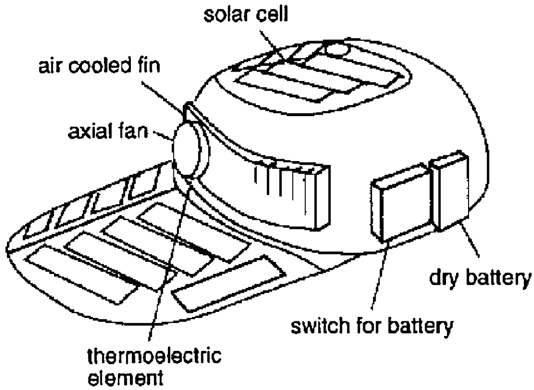

Fig. 5. Schematic of solar-driven thermoelectric cooling headgear(prototype) [24].

used for the air-conditioning of a greenhouse in a sunny region of Spain used for growing tomatoes. Supposed the optimal conditions for growing tomatoes are fixed between 13 °C to 16 °C at night and from 22 °C to 26 °C during the day, and the maximum and minimum biological temperatures are 30 °C and 2 °C respectively and the optimum relative humidity is between 55% and 60%, the total surface of the required active thermal wall composed of eight thermoelectric pairs (Each thermoelectric chain has seven thermoelectric pairs) will be of 105.1 m^2 with a height of 1.5 m approximately for a 540 m^3 greenhouse.

The solar-driven thermoelectric air conditioners are usually used to provide indoor thermal comfort for people, recently a personal solar-driven thermoelectric cooling application for outdoor use was also reported. T. Hara et al. developed a solar-driven thermoelectric cooling headgear to cool the forehead and provide thermal comfort for people in cases of sitting, walking and bicycling. The schematic of this kind of headgear is shown in Fig. 5. In this system, a thermoelectric element was set under the root of brim to cool the forehead by the cold side, and solar cells were mounted on the top and the brim of the headgear to drive the thermoelectric element. A large aluminum fin and an axial cooling fan were attached at the hot side of thermoelectric elements to be as heat sink. Three models with different purpose were developed. It was reported that the maximum temperature difference of 4–5 °C for thermal comfort can be provided when sixteen pieces of silicon crystal solar cell($0.6V_{max} \times 0.4A_{max}$), which were 20×60 mm and weighed 2 g each, and a 30×30 mm thermoelectric module($3A_{max} \times 14V_{max}$) were used. The minimum weight headgear of 135 g can be made when three pieces of amorphous flexible paper-type solar cells($0.35V_{max} \times 1.5A_{max}$), which were 90×230 mm and weighed 5 g, a 40×40 mm thermoelectric module($4.0A_{max} \times 17.5V_{max}$) and a lighter electric fan were used [24].

3. Solar-driven thermoelectric power generators

The thermoelectric devices can utilize solar thermal power and waste heat to generate electricity, and are friendly to the environment as no any refrigerant gas is used, so they have attracted increasing attention as a green and flexible source of electricity able to meet a wide range of power requirements. Furthermore, they have an obvious advantage when used in a cogeneration system which simultaneously provides electric power and useful heat (extracted from the cold side of the system), The development of thermoelectric power

generation is always the worldwide focal point for concern since 1950s, in particular, after the energy crisis in 1970s. Thermoelectric power generation, including low power generation and high power generation, has been described in numerous publications [6,25], a complete review on thermoelectric power generation is out of the space of this paper.

A solar-driven thermoelectric power generator, in its simplest form, consists of a thermoelectric generator and a thermal collector. The solar heat is adsorbed by the thermal collector, and then concentrated and conducted over the thermoelectric generator by a fluid pipe. The thermal resistance of the thermoelectric generator causes a temperature difference that is proportional to the heat flux from the absorber of the thermal collector to the fluid. The electric power generated by the thermoelectric generator is proportional to the temperature difference.

Chen (1996) made a thermodynamic analysis of solar-driven thermoelectric power generator based on a well-insulated flat plate collector. A thermodynamic model including four irreversibilities is used to investigate the optimal performance of a solar-driven thermoelectric generator. The efficiency of the system is derived and taken as an objective function for optimization. Some important curves, such as the efficiency of the system versus the operating temperature of the solar collector, the reduced current, and the load resistance, are obtained [26]. However, the well-insulated flat plate collector, in practice, may be difficult to achieve.

Gunter Rockendorf, et al. (2000) compared detailedly the performance of a solar-driven thermoelectric power generator combining a solar thermal collector with a thermoelectric generator, and a solar-driven PV-hybrid power generator combining the photovoltaic cells with a thermal collector, and simulated their behavior in typical domestic hot water systems. The solar-driven PV-hybrid power generator produces the heat and the electricity were produced in parallel, while the solar-driven thermoelectric power generator produced first, and then to transfer this heat to the thermal resistance of the thermoelectric generator where the heat was partly be transformed into electricity. So the thermal efficiency of the solar-driven thermoelectric power generator is low, and also the energy conversion factor is low. It was reported that the improved extrapolated solar-driven thermoelectric collector ($5\,m^2$ evacuated tubular collector) would lead to an electricity gain of 50 kWh/a and meet the improvement thermal demand with a solar fraction of 53%, while the solar-driven PV-hybrid thermoelectric collector with the same collector area of $5\,m^2$ delivers around 450 kWh/a and covers the thermal demand by 24% which is nine-times higher than the electricity production of the advanced extrapolated thermoelectric collector. The energy conversion efficiency of a solar-driven thermoelectric power generator is only 2.3–3.2%, but the energy conversion efficiency of PV-hybrid system can reach 10%. Therefore, the authors concluded that the current solar-driven thermoelectric collectors will only be of interest for special applications and special purposes [27].

The solar-driven PV-hybrid collector and radioisotope thermoelectric generators, where the thermal energy from the natural decay of radioisotope ^{238}Pu is used as stable heat source, are always used as power sources in aerospace program since 1961, but the damage of solar cells caused by high incident solar heat flux and the environment problem in case of explosion of satellites and spacecrafts during the ascent limited the use of both technologies in near sun missions. Recently, CoSb3 based-skutterudites was found to have much better thermoelectric performances than those of the established Si–Ge based alloys, making them very attractive in a variety of applications in the field of space and waste heat

recovery [28]. A skutterudites-based solar thermoelectric generator was proposed to replace the solar cell or the radioisotope thermoelectric generator currently used to power satellites and spacecrafts flying near to the sun [29,30]. H. Scherrer, et al. presented a series of mathematical models based on the optimal control theory to assess electric performance of a skutterudites-based solar thermoelectric generator as a function of sun–spacecraft distance, and optimize its design parameters (such as dimensions, weight and so on.) when operating at a distance of 0.45 a.u. from the sun, for 400 W electrical output power and for a required load voltage of 30 VDC. The simulation results indicated that the skutterudites-based solar thermoelectric generator offered attractive performance features as primary or auxiliary power source for spacecraft in near-Sun missions. The skutterudite materials are however still under development and need to be fully characterized in terms of performance and long life operation [29,30].

During the last decade, a new roof design concept termed "The Thermoelectric Roof Solar Collector (TE-RSC)" was proposed by Building Scientific Research Center (BSRC) to reduce roof heat gain and improve indoor thermal comfort. TE-RSC combines the advantages of roof solar collector and thermoelectrics to act as a power generator [31]. The schematic of TE-RSC is shown in Fig. 6.

The main components of the TE-RSC are a transparent glass, air gap, a copper plate, thermoelectric modules and a rectangular fin heat sink. The incident solar radiation heats the copper plate to create a temperature difference between the TE modules, which subsequently can generate a direct current. This resulted current was used to run a fan for cooling the TE and improving the indoor thermal conditions. The lab-scale investigation results indicated that that this new roof design with 0.525 m^2 surface area and 10 thermoelectric modules, can generate about 1.2 W under solar radiation intensity of about 800 W/m^2 at 30–35 °Cambient temperature. The corresponding air velocity generated by the ventilation fan was about 1.7 m/s [31]. The subsequent simulation results using real house configuration showed that a TE-RSC unit of 0.0525 m^2 surface area could generate about 9 W under 972 W/m^2 solar radiation and 35 °C ambient temperature. The induced air change rate varied between 20 and 45 ACH and the corresponding ceiling heat transfer rate reduction is about 3–5 W/m^2. The annual electrical energy saving was about 362 kWh.

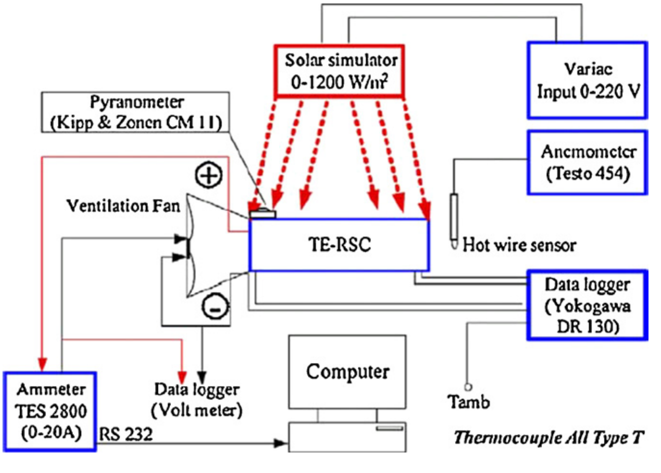

Fig. 6. Schematic of the thermoelectric roof solar collector (TE-RSC) [31].

Finally, economical calculations indicated that the payback period of the TE-RSC is 4.36 years and the internal rate of return is 22.05%. The electrical conversion efficiency of the proposed TE-RSC system is 1–4%, so the authors concluded that it seems to be an attractive new alternative for power generation only in remote areas, roof heat gain reduction and indoor ventilation improvement for hot and humid area [32].

For a typical solar-driven thermoelectric generator, we have the following approximate relation:

$$\eta = \frac{1}{4} Z \Delta T$$

$$Z = \mathrm{S}^2/\mathrm{Kr}$$

Here η is the efficiency of the generator system, Z is the figure-of-merit, ΔT is temperature difference across the thermoelectric modules, S, r and K are the Seeback coefficient, the electric resistance and the thermal conductance, respectively.

It is apparent that in order to achieve a high efficiency η, ΔT should be as high as possible, and the thermoelectric materials should possess a high figure-of-merit Z, that is, a high Seeback coefficient but low electric resistance (or a high electrical conductivity) and low thermal conductivity.

In order to improve efficiency of the system, a great deal of experimental research and computer simulation have been done. All these works are mainly involved in the following four aspects.

Firstly, some works focused on the improvement of the solar concentrator to concentrate the solar heat to hot side of the thermoelectric generator much better, and then to improve the thermal transmission efficiency of solar collector. The thermoelectric materials with high quality are relatively expensive, and therefore a thermoelectric generator should be designed to enable minimal use of thermoelectric materials for a given power requirement. To concentrate the solar radiation so as to create a high temperature gradient across the thermoelectric device is an efficient method. Many studies on the single line focusing parabolic trough (PTC), the Compound Parabolic Concentrator (CPC) and the two-stage concentrator have been done before [33]. The two-stage solar concentrator is designed to use a PTC or PTC with low concentration factor in conjunction with a secondary receiver to further concentrate the incident solar radiation. It can more efficiently concentrate the solar radiation, so more close attention was paid to it [33]. Some two-stage solar concentrators are designed specially for photovoltaic conversion [34]. Mills first designed a two-stage solar concentrator used for both photovoltaic conversion and thermal processes [35]. More recently, Sidding A. Omer presented a design and performance evaluation for a two stage solar concentrator, which is comprised of a primary one axis PTC and a second stage made of a symmetrical CPC, mounted at the focus of the primary, and is well suited to commercially available thermoelectric devices for small scale power generation [36]. In 1993, the Solar Orbit Transfer Vehicle (SOTV) program sponsored by the US Air Force Research Laboratory (AFRL) proposed to use an advanced lightweight deployable mirrored concentrator to focus solar energy onto a compact absorber, which is in turn heated to more than 2200 K. This heat can made the attached thermionic or alkali metal thermoelectric converter (AMTEC) power converters generate 20 to 100 kilowatts (kW) of electricity, which is suitable for large-scale application such as cargo missions to the Moon and Mars [37].

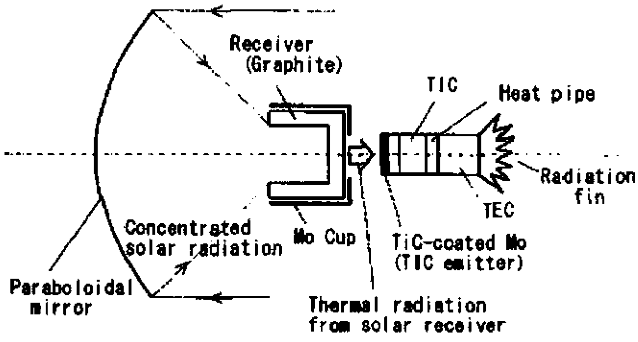

Fig. 7. Schematic of a solar-powered thermionic/thermoelectric conversion system [38].

Secondly, some works have been done to improve the hot side temperature of a solar-driven thermoelectric generator, and thereby generate a bigger temperature difference across the thermoelectric device. H. NAITO, et al. developed a solar-powered high-efficiency thermionic/thermoelectric conversion system which combines a thermionic converter (TIC) with a thermoelectric converter (TEC) to use thermal energy efficiently. A cylindrical cavity-type solar receiver constructed from graphite was designed and heated in a vacuum by using the solar concentrator at Tohoku University. Once the TIC emitter is uniformly heated up to 1800 K, a hot side temperature of 1800 K can be achieved[38]. The schematic of a solar-powered thermionic/thermoelectric conversion system is shown in Fig. 7.

Thirdly, the thermoelectric performance of materials is closely related with the efficiency of a solar-driven thermoelectric generator. Over the past few years, much effect has been devoted to the development of materials with high Z values. Currently a number of thermoelectric materials are available commercially. One of these is PbTe which has found to be used in power generation in the temperature of 230– 530 °C. Bi_2Te_3/Sb_2Te is mainly used for cooling purposes and low-scale power generation in the temperature from room temperature to about 130 °C, while SiGe is more suitable for the applications in the temperatures above 530 °C, particularly for auxiliary power supply in space satellites, using isotope fuels. Skutterudites based on $CoSb_3$ have been recently promoted as promising new thermoelectric materials to replace the established SiGe based alloys [29]. The exploitation of new thermoelectric materials with high Z values is under study, in the meantime, some works are also being done to enhance the thermoelectric performance of currently developed. The works in this field have been discussed in numerous publications [39].

Fourthly, computer simulation is widely used for design optimization of a solar-driven thermoelectric generator, and a variety of mathematical models have been established [40]. The optimal control theory is currently reported to be the most suitable for evaluating the performance of a solar-driven thermoelectric generator. More recently, H. Scherer developed a numerical simulation based on the optimal control theory to assess the performances, dimensions and weight characteristics of skutterudite-based solar thermoelectric generators (STG) for satellite missions at distances close to the Sun [29]. S. A. Omer presented an improved theoretical model of a solar-driven thermoelectric generator, which takes into account the effect of all the parameters contributing to the heat transfer process associated with the thermoelectric device. This model has been developed for

geometrical optimization of the thermoelectric element legs and prediction of the performance of an optimum device in power generation mode [40].

4. Conclusions

The development and applications of two solar-driven thermoelectric technologies (i.e., solar-driven refrigeration and solar-driven thermoelectric power generation) are presented in this paper. The currently existing drawbacks of the solar-based thermoelectric technologies are also presented as well as methods to improve and evaluate the performance of the solar-driven thermoelectric devices. Additionally, typical applications of two solar-driven thermoelectric technologies are described in order to show to the reader the extent of their applicability. It should be noted that the applications of solar-driven thermoelectric technologies are not limited to the areas mentioned in this paper. There are many other applications which are not described here either because they are not fully developed or are just in germ. The application areas described in this paper show that solar-driven thermoelectric technologies could be used in a wide variety of fields. They are attractive technologies that not only can serve the needs for refrigeration, air-conditioning applications and power generation, but also can meet demand for energy conservation and environment protection. But due to the low COP or low energy conversion efficiency of the solar-driven thermoelectric devices, currently the solar-driven thermoelectric devices can only be used in limited applications, such as aerospace, military or cases in which the cost is not the main consideration. New thermoelectric materials with high thermoelectric performance, more modern collecting technology and transferring technology relating with solar energy, and more advanced optimization design of the solar-driven thermoelectric devices are being ardently anticipated.

References

[1] Ewert, Michael K. Terrestrial and Aerospace Solar Heat Pump Development: past, present and future, ASME paper at Solar '98, Albuquerque, NM; 1998.

[2] Stockholm, JG, Pujol-Soulet, L, Sternat, P. Prototype thermoelectric air conditioning of a passenger railway coach. IECEC Catalog, No. 82, Arlington, USA; 1982.

[3] Stockholm JG, Despres JP. Large Scale Thermoelectric Cooling. Paris, France: Publications TNEE—Air industrie thermoelectrics; 1986.

[4] Bojic M, Savanovic G, Trifunovic N, Radovic L, Sljic D. Thermoelectric cooling of a train carriage by using a coldness-recovery device. Energy 1997;22(5):493–500.

[5] Tritt TM, Kanatzidis MG, Lyon Jr HB, Mahan GD. Thermoelectric materials—new directions and approaches. Warrendale, PA: Materials Research Society; 1997.

[6] Riffat SB, Xiaoli Ma. Thermoelectrics: a review of present and potential applications. Appl Therm Eng 2003;23:913–35.

[7] Riffat SB, Guoquan Qiu. Comparative investigation of thermoelectric air-conditioners versus vapour compression and adsorption air-conditioners. Appl Therm Eng 2004;24:1979–93.

[8] Bansal PK, Martin A. Comparative study of vapour compression, thermoelectric and absorption refrigerators. Int. J. Energy Res. 2000;24:93–107.

[9] Wimolsiri Pridasawas, Solar cooling and sustainable refrigeration, http://www.egi.kth.se/proj/courses/4A1623/files/ARHPTSustainRefrig2005WP.pdf.

[10] Altenkrich E. Uber den Nutzeffekt der Thermosaule. Physikalische Zeiltschrift 1909:560–8.

[11] Sofrata H. Solar Thermoelectric Cooling System. In: James SW, Khoshaim BH, Mallory R, Meiners A, editors. Solar Buildings. Missouri: Midwest Research Institute; 1984. p. 59–76.

[12] Rajapakse RMAD. Refrigeration: the solar photovoltaic option, http://www.ieiglobal.org/ESDVol1No2/solarrefrigeration.pdf.
[13] Sofrata H. Heat rejection alternatives for thermoelectric refrigerators. Energy Convers Manage 1996;37(3):269–80.
[14] Wang RZ, Dai YJ. Solar thermoelectric refrigerator. Patent No. 01239142, 2001; 5, China.
[15] Dai YJ, Wang RZ, Ni L. Experimental investigation and analysis on a thermoelectric refrigerator driven by solar cells. Sol Energy Mater Sol Cells 2003;77:377–91.
[16] Michael K Ewert, Marty Agrella, Dan DeMonbrun, et al. Experimental evaluation of a solar PV refrigerator with thermoelectric, stirling and vapor compression heat pumps, http://www.globalcooling.com/pdfs/8_experimentaleval.pdf.
[17] Omer SA, Riat SB, Ma X. Experimental investigation of a thermoelectric refrigeration system employing a phase change material integrated with thermal diode (Thermosyphons). Renewable Energy 2001;21:1265–71.
[18] Tavaranan S, Das A, Aurora P, Trelles JP. Design of a standalone portable solar-powered thermoelectric vaccine refrigerator using phase change material as thermal backup Solar Engineering Program. USA: University of Massachusetts Lowell; 2002.
[19] Juan Trelles P, Duy John J. Numerical simulation of porous latent heat thermal energy storage for thermoelectric cooling. Appl Therm Eng 2003;23:1647–64.
[20] Costa M, Buddhi D, Oliva A. Numerical simulation of a latent heat energy storage system with enhanced heat conduction. Energy Convers Manage 1998;3(4):319–30.
[21] Leoni N, Amon CH. Transient thermal design of wearable computers with embedded electronics using phase change materials. ASME HTD 1997;437(part 5):241–50.
[22] Mei VC, Chen FC, Mathiprakasam B, Heenan P. Study of solar-assisted thermoelectric technology for automobile air conditioning. J Sol Energy Eng, Trans ASME 1993;115(4):200–5.
[23] Jorge Vázquez, Miguel A Sanz-Bobi, Rafael Palacios, Antonio Arenas. An Active Thermal Wall Based on Thermoelectricity, http://www.iit.upco.es/palacios/thermo/ets2001-window.pdf.
[24] Hara T, Azuma H, Shimizu H, Obora H, Sato S. Cooling performance of solar cell driven, thermoelectric cooling prototype headgear. Appl Therm Eng 1998;18:1159–69.
[25] Rowe DW, et al. CRC Handbook of Thermoelectrics. Boca Raton, FL: CRC Press.
[26] Jincan Chen. Thermoelectric analysis of a solar-driven thermoelectric generator. http://www.paper.edu.cn/scholar/known/chenjincan/chenjincan-5.pdf.
[27] Rockendorf Gunter, Sillmann Roland, Podlowski Lars, Litzenburger Bernd. PV-hybrid and thermoelectric collectors. Solar Energy 1999;67(4–6):227–37.
[28] Nolas GS, Sharp JW, Goldsmid JH. Thermoelectrics: basic principles and new materials developments. Heidelberg: Springer; 2001.
[29] Scherrer H, Vikhor L, Lenoir B, Dauscher A, Poinas P. Solar thermoelectric generator based on skutterudites. J Power, Sources 2003;115:141–8.
[30] Lenoir B, Dauscher A, Poinas P, Scherrer H, Vikhor L. Electrical performance of skutterudites solar thermoelectric generators. Appl Therm Eng 2003;23:1407–15.
[31] Maneewan S, Khedari J, Zeghmati B, Hirunlabh J, Eakburanawat J. Investigation on generated power of thermoelectric roof solar collector. Renewable Energy 2004;29:743–52.
[32] Maneewan S, Hirunlabh J, Khedari J, Zeghmati B, Teekasap S. Heat gain reduction by means of thermoelectric roof solar collector. Solar Energy 2005;78:495–503.
[33] Kalogirou Soteris A. Solar thermal collectors and applications. Prog Energy combust Sci 2004;30:231–95.
[34] Brunotte M, Goetzberger A, Blieske U. Two stage concentrator permitting concentration factors up to 300X with one axis tracking. Solar Energy 1996;50(3):285–300.
[35] Mills DR. Two stage tilting solar concentrators. Sol Energy 1980;25:505–9.
[36] Omer Siddig A, Infield David G. Infield, design and thermal analysis of a two stage solar concentrator for combined heat and thermoelectric power generation. Energy Convers Manage 2000;41:737–56.
[37] Kessler Thomas L. Solar thermal OTV-applications to reusable and expendable launch vehicles. Acra Astronautica 2000;47(2–9):215–26.
[38] Naito H, Kohsaka Y, Cooke D, Arashi H. Development of a solar receiver for a high-efficiency thermionic/thermoelectric conversion system. Solar Energy 1996;58(4–6):191–5.
[39] Yang J, Aizawa T, Yamamoto A, et al. J Alloys Comp 2000;309:225.
[40] Omer SA, Infield DG. Design optimization of thermoelectric devices for solar power generation. Sol Energy Mater Sol Cells 1998;53:67–82.